Band-Limited Guidance for the Joint Precision Airdrop System

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Figure 1 – JPADS-2K During Flight Test (US Army Photo by Steve Tavan)

Abstract

The Natick Soldier Research Development and Engineering Center has been leading an effort to develop precision guided airdrop systems to accommodate cargo weights from 80 pounds to 42,000 pounds. This family of systems, called the Joint Precision Airdrop System (JPADS), consists of an Army-led set of aerodynamic decelerators and companion flight software available for the entire JPADS family. The software is developed by Draper Laboratory and is fully government (US Army) owned. This paper describes Draper's terminal guidance technique for the JPADS decelerators, band-limited guidance, and summarizes the performance we have observed in more than three years of extensive flight testing throughout the weight range.

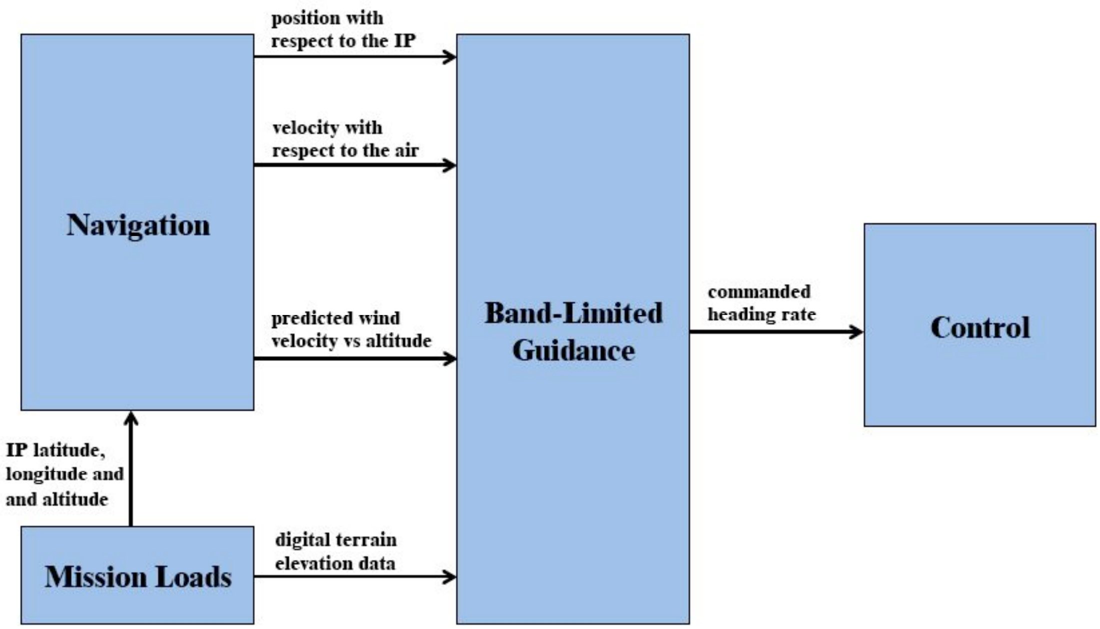

Figure 2 – Band-Limited Guidance Context

Figure 2 shows the interfaces to band-limited guidance. Navigation provides current position coordinates with respect to the desired impact point, estimated north, east and down coordinates of system velocity with respect to the air, and a table of predicted north and east coordinates of wind velocity as a function of altitude. An onboard database provides access to maps of terrain elevation. The guidance algorithm generates heading rate commands that are sent to control.

Band-limited guidance makes the fundamental assumption that commanded heading rate $u(h)$ at altitude h above the IP has the following form:

$$u(h) = \sum_{k=0}^{N} u_k \frac{sin(\pi(h - h_0 - k\,\Delta h)/\Delta h)}{\pi(h - h_0 - k\,\Delta h)/\Delta h} \qquad (1)$$

The parameters $u_0, u_1, \ldots, u_N$ are the commanded heading rates at $N+1$ equally spaced *control point altitudes* $h_0, h_0 + \Delta h, \ldots, h_0 + N\,\Delta h$. JPADS systems use $N = 2$ (three control points) or $N = 3$ (four control points).

System sink rate v_z during final approach is approximately constant, so commanded heading rate is a band-limited function of time with bandwidth not exceeding the Nyquist frequency $v_z/(2\Delta h)$. This is the reason for the name "band-limited guidance". Control point separation Δh is chosen so that the bandwidth of the commanded heading rate signal is well within the bandwidth of the closed loop system the guidance algorithm is commanding. For JPADS systems, v_z is typically on the order of 5 m/s and Δh is typically 150 meters, so bandwidth of the commanded heading rate is on the order of 1/60 Hz.

For each choice of control point heading rates $u_0, u_1, \ldots, u_N$ we can predict the system trajectory by integrating the system kinematic equations, which have the simple form

$$
\begin{aligned}
\dot{x} &= v_x + w_x(h) \\
\dot{y} &= v_y + w_y(h) \\
\dot{h} &= -v_z \\
\dot{v}_x &= -u(h)\, v_y \\
\dot{v}_y &= +u(h)\, v_x
\end{aligned}
\tag{2}
$$

Here x and y denote the north and east coordinates of position with respect to the desired impact point, v_x and v_y denote the north and east components of velocity with respect to the air, $w_x(h)$ and $w_y(h)$ denote the predicted north and east components of wind velocity at altitude h, v_z is system sink rate (assumed constant), and $u(h)$ is commanded heading rate at altitude h computed using equation (1). We integrate the kinematic equations from the current navigated state to predicted impact with the ground, using the table of predicted wind velocity vs altitude and the map of terrain elevation (digital terrain elevation data). For efficiency, the Runge-Kutta integrator is implemented using carefully scaled integer arithmetic, and the function $sinc(x) = sin(\pi x)/(\pi x)$ needed in equation (1) is evaluated by lookup in a pre-computed table.

Each choice of control point heading rates $u_0, u_1, \ldots, u_N$ has a corresponding *cost,* which is a function of the predicted state at impact, computed by integrating equations (2). For JPADS, the cost function is quadratic in the north, east and down coordinates of relative position with respect to the desired IP and quadratic in the sine of half the error in final heading.

The band-limited guidance algorithm uses Nelder-Mead simplex search to select control point heading rates that minimize cost. To correct for early errors in horizontal wind prediction, for the lack of a vertical wind model, and for other errors in modeling and navigation, these guidance calculations are repeated at 1 Hz, using current navigated position, velocity with respect to the air, and updated wind predictions.

Figure 3a shows the final ground-track from all phases of a recent flight test; band-limited guidance is active during the part of the trajectory shown as blue squares. Figure 3b shows how the trajectories selected in successive cycles of band-limited guidance evolve as the system descends. The first of these predicted trajectories is the inner trajectory, shown in black; it's a gradual, smooth hook into the impact point with final heading determined by the wind direction predicted earlier in flight. The trajectories evolve to adapt to variations in predicted wind, unmodeled updrafts and downdrafts, and other variations in system behavior; the last of the predicted trajectories is shown in brown. The trajectory actually flown is shown as black dashes. The system matches its commanded final heading to within 10 degrees and lands 6 meters from the target. Although not shown in the figure, we can show from the final onboard wind estimate that the system comes very close to landing directly into the wind, so has minimum ground speed at impact.

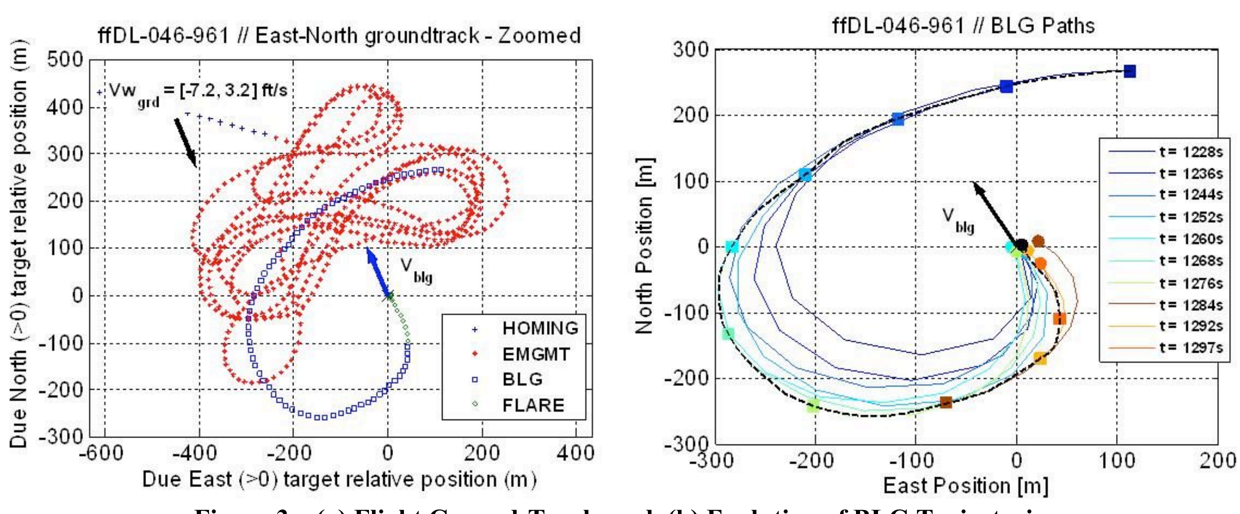

Figure 3 – (a) Flight Ground-Track and (b) Evolution of BLG Trajectories

A detailed discussion of the results we've obtained using band-limited guidance in JPADS systems, including our experience with various 0.5K, 2K and 10K systems, will be given in the full paper.